Atmospheric neutrinos: phenomenological summary and outlook

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The predictions of the atmospheric ν event rates are affected by significant uncertainties, however the evidence for the 'disappearance' of ν_μ's and $\overline{\nu}_\mu$'s obtained by SK (and other underground detectors) is robust and cannot be accounted in the framework of the minimum standard model without assuming very large *ad hoc* experimental systematic effects. The existence of 'new physics' beyond the standard model is therefore close to be established; ν oscillations provide a very good fit to all data. The theoretical uncertainties do have an important role in the detailed interpretation of the data, and in the estimate of oscillation parameters.

1 Evidence for the disappearance of muon neutrinos

The data of Super–Kamiokande (SK)[1,2] and other detectors have given strong evidence that ν_μ's and $\overline{\nu}_\mu$'s 'disappear'. This evidence comes from the observation of three experimental effects: (i) the detection of an up–down asymmetry for the μ–like events, (ii) the detection of a small μ/e ratio, (iii) the detection of a distortion of the zenith angle distribution and a suppression of the ν induced upward going muon flux. The three effects are listed in order of 'robustness' with respect to systematic uncertainties. The statistical significance of the effects in SK, especially for (i) and (ii), is very strong. In the following we will discuss how theoretical uncertainties in the predictions cannot 'reabsorb' the observed effects, but do play a role in the *interpretation* of the data.

2 Systematic uncertainties in the predictions

In the prediction of the event rates for an atmospheric ν experiment one needs to: (i) consider an initial flux of cosmic ray particles, (ii) model the hadronic showers produced by these particles in the Earth atmosphere, (iii) describe the ν cross sections, (iv) describe the detector response to ν interactions (and possible background sources). Here we will consider only the first three 'theoretical' elements of the calculation, and will argue that there are significant uncertainties, that influence the absolute normalization, the shape of the energy spectrum, the angular distribution, and the μ/e ratio of the events. The primary cosmic ray (c.r.) flux has been a major source of uncertainty (see[3] for a detailed discussion) because of the discrepant[a] results obtained by two groups (Webber 79 and LEAP 87) differing by $\sim 50\%$ (see fig. 1). Recently,

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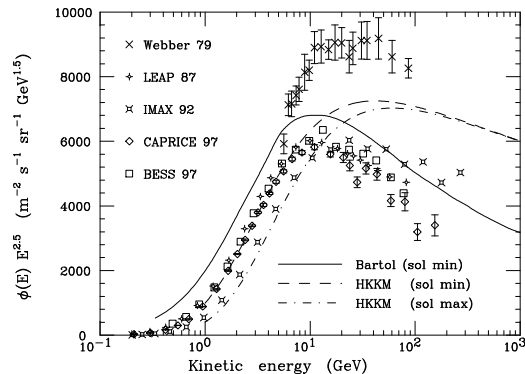[a]It is highly unlikely that the obseved differences are the result of time variations.

Figure 1: Measurements of the c.r. proton flux (points) (see [3] for the references), and the representations used as input in the Bartol [5] and HKKM [4] calculations (lines).

new measurements of the c.r. proton flux have given results consistent with the lower normalization. If the lower normalization is accepted as correct, the uncertainty in the primary c.r. flux can be reduced, however the description of the primary c.r. flux (see fig. 1) used in two calculations of the atmopheric ν fluxes: Honda et al. (HKKM) [4] and Bartol [5] used in predictions for SK and other detectors are then too high (by $\sim 30\%$ and $\sim 10\%$).

A second source important source of uncertainty is our lack of knowledge on the properties of particle production in p–nucleus and nucleus–nucleus interactions. The calculations of Bartol [5] and HKKM [4] use different descriptions for the multiplicity and energy spectrum of the pions produced in p–Nitrogen (Oxygen) interactions. For the same primary c.r. flux, this would result in a $\sim 20\%$ higher ν event rate for the Bartol calculation. Some controversy exists about what description of hadronic interactions is in better agreement with the existing data. An experimental program, studying in detail the structure of particle production in the relevant energy range (a broad region centered at $E_0 \sim 20$ GeV), would result in an improvement in the predictions.

The similar normalization of the two [5,4] calculations is the result of a cancellation between a higher (lower) flux for the c.r. flux, and a lower (higher) ν yield per primary particle for the HKKM (Bartol) calculation. This cancellation, to a large extent, is not casual, but is the consequence of fitting the (same) data on $\mu^{\pm}$ fluxes at ground level. This underlies the importance of these measurements. It is very desirable to repeat them with greater accuracy. High altitude meaurements with balloons [3] also offer a great potential.

A third source of 'theoretical' uncertainty, of comparable importance to

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the other two, is related to the description of σ_ν. At high E_ν, when most of the phase space for ν interactions is in the deep–inelastic region, σ_ν is reliably calculable in terms of well determined parton distribution functions (PDF's). However for $E_\nu \sim 1$ GeV the description of σ_ν is theoretically more difficult. Quasi–elastic scattering is the most important mode, but also events with the production of one or more pions (where the additional particles are undetected or are reabsorbed in the target nucleus) are important contributions to the signal. The production of Δ's and other resonances is important, nuclear effects have to be included. A relatively small modification in the description of a fraction of σ_ν in the SK montecarlo: the choice of a new set of PDF's (GRV94LO replacing the CCFR parametrization) has resulted in an increase of the predicted number of partially contained events by approximately 7% (compare the MC predictions in[1] and[2]). It appears very difficult to calculate accurately σ_ν from first principles in the relevant energy region. The existing data do not determine the absolute value of the cross section and the energy spectrum of the final state lepton better that $\sim 15\%$. Additional data could help in improving the situation. The K2K ν beam with a spectrum not too different from the atmospheric one offers interesting possibilities.

3 Robust properties of the predictions and observed effects

Two properties of the ν fluxes are to a large extent independent from the details of the calculation and provide 'self calibration' methods: (i) the fluxes are approximately up/down symmetric: $\phi_{\nu_\alpha}(E_\nu, \theta) \simeq \phi_{\nu_\alpha}(E_\nu, \pi - \theta)$, (ii) the ν_μ and ν_e fluxes are strictly related to each other because they are produced in the chain decay of the same charged mesons (as in $\pi^+ \to \nu_\mu \, \mu^+$ followed by $\mu^+ \to \overline{\nu}_\mu \nu_e e^+$). Writing $\phi_{\nu_\mu}(E, \theta) = r(E_\nu, \theta) \times \phi_{\nu_e}(E, \theta)$ the factor $r(E_\nu, \theta)$ varies slowly with energy and angle and is quite insensitive to the details of the calculation. These two properties are at the basis of the robustness of the evidence for oscillations. The up–down symmetry follows as a simple and *purely geometrical* consequence from two assumptions: the primary c.r. flux is isotropic, the Earth is spherically symmetric. The c.r. flux at 1 A.U. of distance form the sun is isotropic to a precision better than 10^{-3}, as can be measured observing in a fixed direction and looking for time variations while the Earth rotates. The isotropy is spoiled by the geomagnetic field that bends the particle trajectories and forbids the lowest rigidity ones from reaching the Earth's surface introducing directional (east–west) and location (latitude) effects. These effects vanish at large momentum (see fig. 2). The measurement of an (oscillation independent) east–west effect for atmospheric ν's in agreement with predictions, by SK[6] is an important test, that validates the calculations.
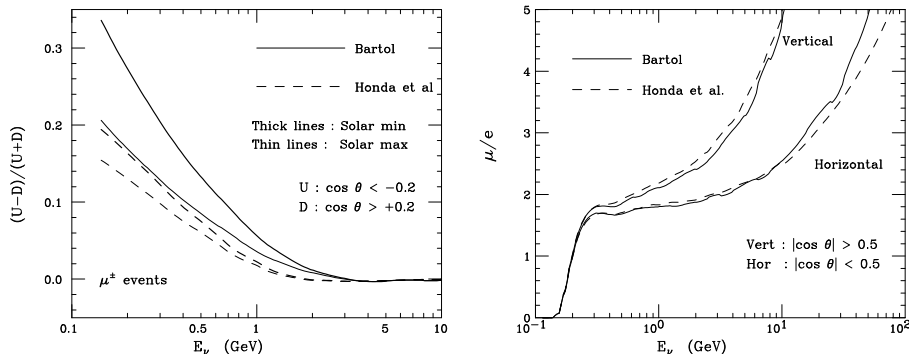
Figure 2: The left panel shows the up/down asymmetry (no–oscillation hypothesis) of cc–interacting ν_μ's and $\overline{\nu}_\mu$'s in the Bartol [5] and HKKM [4] calculations for the Kamioka site. The right panel shows the μ/e ratio for the two models.

Note that at Kamioka (near the magnetic equator) geomagnetic effect have the opposite effect to ν–oscillations, and produce an up–going ν flux *larger* than the down–going one (both magnetic poles are below the detector). At the Soudan mine (near the magnetic pole) the opposite is true. Note also that the predicted asymmetry at low energy (see fig. 2) has some model dependence with the Bartol calculation predicting a higher no–oscillation asymmetry. This is important for the detection of a zenith angle modulation in the Soudan detector and is also relevant for the interpretation of the SK sub–GeV events.

The right panel of fig. 2 shows how different calculations of the atmospheric ν flux predict very similar μ/e ratios. This however refers to a *fixed* value of E_ν. In fig. 3 we show an estimate of the energy distributions of the neutrinos that produce the SK events, note how the distributions for μ and e like events differ. For the multi–GeV samples, a harder ν spectrum, or a faster raise with energy of σ_ν, result in a larger (smaller) increase in the predicted rate of μ–like (e–like) events, therefore in a smaller double ratio R (because of a larger denominator) and finally to a larger Δm^2 (for the same mixing) in the $\nu_\mu \leftrightarrow \nu_\tau$ interpretation to explain the larger suppression. At this conference, SK has presented a new estimate for the (90% C.L.) allowed region in the $(\sin^2 2\theta, \Delta m^2)$ plane for the $\nu_\mu \leftrightarrow \nu_\tau$ hypothesis, considering a larger exposure and a slightly modified MC calculation. The new [2] allowed region is smaller that the previously published one [1] not including the interval $|\Delta m^2| \simeq 0.5$–1.0×10^{-3} eV^2, a result very encouraging for the LBL programs. The use of a new set of PDF's in the description of σ_ν has the qualitative effect to enhance the contribution of high energy events, and for the argument outlined above is an important contribution to the exclusion of the low Δm^2 interval.
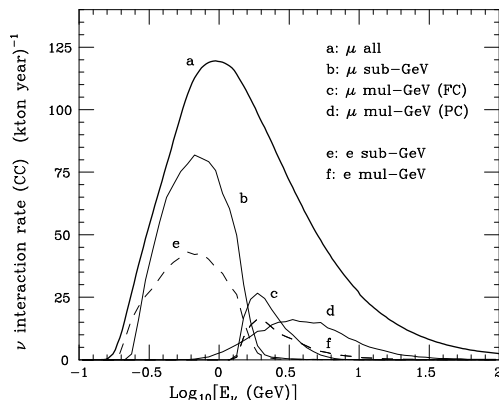
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Figure 3: Approximate energy distributions of interacting neutrinos for different classes of events in SK. Note the difference in the shape of the response for μ–like and e–like events

4 Outlook

The detection of oscillations in atmospheric ν experiments is a result of great importance. The detailed study of this phenomenon and the precise measurement of the parameters (masses and mixing) involved is a great opportunity and a difficult challenge. SK has a remarkable potential to obtain more convincing evidence and more precise measurements. New data on primary c.r. fluxes, hadron–nucleus interactions, ν–nucleus interactions and $\mu^{\pm}$ fluxes could help the interpretation of present and future data. Long baseline ν beams, have also the potential to confirm the results and study the phenomenon. This could happen very soon with the K2K project, the existence of two (similar to each other) LBL projects in the US and in Europe is seen by some as a beneficial case of scientific competition, and by others as a dangerous waste of resources.

References

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